

**Final report on USGS/NEHERP proposal 02HQGR0047  
Rock Deformation and Seismicity on Heterogeneous Faults**

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**Non Technical Summary**

Studies done under this project were focused on four directions. The **first** involved analysis of six new fracture experiments conducted in the lab of Dr. Dave Lockner to provide constraints to the damage rheology model of Lyakhovsky, Ben-Zion, and Agnon (JGR, 1997). The analysis done so far focused on attempting to explain the data with simplified calculations involving a uniform damage evolution (i.e., a model with a single damage degree-of freedom). The results show good overall agreement between model predictions and observations until the final stage of deformation associated with damage localization. Analysis of the latter stage requires 3D calculations and will be done in continuing work. The **second** research direction was a study of intermittent criticality in a quasi-static model of a discrete fault system in a 3D elastic half-space. The results suggest that large earthquake cycles on heterogeneous faults are associated with intermittent criticality, produced by spontaneous evolution of stress heterogeneities toward a level of disorder having a broad range of scales. The stress evolution and development of large earthquake cycles may be tracked with seismicity functions. The **third** direction focused on incorporation of quasi-dynamic computational procedure and lab-based  $\log(t)$  healing in the above quasi-static model. The **forth** direction involved development of dynamic system analysis and prediction methodology based on ground deformation.

Results from the last three research directions were submitted for publications and the abstracts from those papers are given below.

**Ben-Zion, Y., M. Eneva, and Y. Liu, Large Earthquake Cycles and Intermittent Criticality On Heterogeneous Faults Due To Evolving Stress and Seismicity, J. Geophys. Res., 2003.**

**Abstract.** We analyze evolving stress and seismicity generated by three realizations of a discrete model of a strike-slip fault in a 3D elastic half-space using five functions of stress and five functions of seismicity. The first model (F) has realistic dynamic weakening (static minus dynamic frictions), the second (FC) has zero critical dynamic weakening, and the third (SYS) is constrained to produce only system-size events. The results for model F show cyclical development, saturation, and destruction of fluctuations and long range correlations on the fault, punctuated by the system-size events. The development stage involves evolution of stress and seismicity to distributions having

broad ranges of scales, evolution of response functions toward scale-invariant behavior, increasing seismicity rate and event sizes, and increasing hypocenter diffusion. Most functions reach asymptotically stable values around 2/3 of the cycle and then fluctuate until one event cascades to become the next large earthquake. In model FC the above evolution is replaced by scale-invariant statistical fluctuations, while in model SYS the signals show simple cyclic behavior. The results suggest that large earthquake cycles on heterogeneous faults with realistic positive dynamic weakening are associated with intermittent criticality, produced by spontaneous evolution of stress heterogeneities toward a critical level of disorder having a broad range of scales. The stress evolution and development of large earthquake cycles may be tracked with seismicity functions.

**Zöller, G., M Holschneider, M. and Y. Ben-Zion, Quasi-static and Quasi-dynamic modeling of earthquake failure at intermediate scales, *Pure Appl. Geophys.*, 2004.**

**Abstract.** We present a model for earthquake failure at intermediate scales (space: 100 m - 100 km, time:  $100 \text{ m} / v_{\text{shear}} \sim 1000$ 's of years). The model consists of a segmented strike-slip fault embedded in a 3-D elastic solid as in the framework of Ben-Zion and Rice (1993). The model dynamics is governed by realistic boundary conditions consisting of constant velocity motion of the regions around the fault, static/kinetic friction laws with possible gradual healing, and stress transfer based on the solution of Chinnery (1963) for static dislocations in an elastic half-space. As a new ingredient, we approximate the dynamic rupture on a continuous time scale using a finite stress propagation velocity (quasi-dynamic model) instead of instantaneous stress transfer (quasi-static model). We compare the quasi-dynamic model with the quasi-static version and its mean field approximation, and discuss the conditions for the occurrence of frequency-size statistics of the Gutenberg-Richter type, the characteristic earthquake type, and the possibility of a spontaneous mode switching from one distribution to the other. We find that the ability of the system with a given cell size to undergo a spontaneous mode switching, depends on the range of the stress transfer interaction. We also introduce time-dependent  $\log(t)$  healing and show that the results can be interpreted in the phase diagram framework. To have a flexible computational environment, we have implemented the model in a modular C++ class library.

**Anghel, M., Y. Ben-Zion and R. R. Martinez, Dynamical system analysis and forecasting of deformation produced by an earthquake fault, *Pure Appl. Geophys.*, 2004.**

**Abstract.** We present a method of constructing low-dimensional nonlinear models describing the main dynamical features of a discrete 2D cellular fault zone, with many degrees of freedom, embedded in a 3D elastic solid. A given fault model realization is characterized by a set of parameters that describe the dynamics, rheology, property disorder and fault geometry. Depending on the location in the model parameter space, we show that the coarse dynamics of the fault can be confined to an attractor whose dimension is significantly smaller than the space in which the dynamics takes place. Our strategy of system reduction is to search for a few coherent structures that dominate the

dynamics and to capture the interaction between these coherent structures. The identification of the basic interacting structures is obtained by applying the Proper Orthogonal Decomposition (POD) to the surface deformations fields, that accompany strike-slip faulting accumulated over equal time intervals. We use a feed-forward artificial neural network (ANN) architecture for the identification of the fault dynamics in the reduced representation of the most energetic coherent structures. The ANN is trained using a standard back-propagation algorithm to predict (map) the values of the observed state at a future time given the observed state at the present time. This ANN then provides an approximate dynamical model for the fault. The map can be evaluated once to provide short term predictions or iterated to obtain prediction for the long term fault dynamics.

### **Publications Supported by this grant**

#### *Papers:*

- Anghel, M., Y. Ben-Zion and R. R. Martinez, Dynamical system analysis and forecasting of deformation produced by an earthquake fault, *Pure Appl. Geophys.*, **161**, 2023-2051, 2004.
- Ben-Zion, Y., M. Eneva, and Y. Liu, Large Earthquake Cycles and Intermittent Criticality On Heterogeneous Faults Due To Evolving Stress and Seismicity, *J. Geophys. Res.*, **108**, NO. B6, 2307, doi:10.1029/2002JB002121, 2003.
- Zöller, G., M. Holschneider and Y. Ben-Zion, Quasi-static and Quasi-dynamic modeling of earthquake failure at intermediate scales, *Pure Appl. Geophys.*, **161**, 2103-2118, 2004.

#### *Abstracts:*

- Anghel, M., Y. Ben-Zion I. G. Kevrekidis and R. R. Martinez, From mechanistic to phenomenological models: Integrated forecasting and modeling of earthquake dynamics, *Extended abstract* for the ACES meeting, 2002.
- Ben-Zion, Y., M. Eneva, and Y. Liu, Stress Evolution, Seismicity, and Intermittent Criticality on a Fault During a Large Earthquake Cycle, *Math. Geophys. Meeting*, 2002.
- Zöller, G., Holschneider, M., Ben-Zion Y., Quasi-dynamic deterministic and stochastic modeling of earthquake failure at intermediate scales, *Extended abstract* for the ACES meeting, 2002.